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Practical Wind Speed and Rain Rate Prediction from Underwater Noise

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ABSTRACT

Equations for estimating wind speed and rain rate from underwater noise are derived in this paper. Data from both this study and other published studies were used.

Data for this study were collected during October and November 1988 off south Florida in 50 m of water. Noise levels at 12 frequencies from 0.5 to 30 kHz were recorded, edited, and grouped. Regression was used to derive site-specific prediction equations for wind speed and rain rate. The best-fit equations were all linear in sound-pressure level. The best wind-speed predictor, without rain, was the 2 kHz frequency. The best rain-rate predictor was 8 kHz. The best wind-speed predictor, during rain, required both the 2 and 8 kHz frequencies.

Data from this study were then combined with data from other studies. Regression was used to derive "universal" prediction equations. These equations were also linear in sound-pressure level. They also required the same predictor frequencies (2 and 8 kHz) as the site-specific equations. However, they were much less accurate, especially for predicting rain rate.

For the most accurate predictions of wind speed and rain rate from underwater noise, site-specific equations should be derived and used.

ACKNOWLEDGMENTS

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CONTENTS

PRACTICAL WIND SPEED AND RAIN RATE PREDICTION FROM UNDERWATER NOISE

I. INTRODUCTION

A. The Problem

Wind and rain are two of the most important variables in weather forecasting. High winds put both life and property at risk. They damage structures, and threaten the aviation, maritime shipping, and fishing industries. Heavy rains are equally destructive. They produce flooding, increase accidents, and stall construction.

Before weather services can forecast these two variables, they must first measure them. On land, their measurement is fairly straightforward. Anemometers and rain gages have been available for decades. These devices are mounted on a small (to avoid interference), sturdy (to avoid motion) structure in an open area (to avoid local effects). At sea, on the other hand, wind and rain measurements are difficult. They have to be measured from ships or buoys. These platforms are typically unstable and large enough to interfere with the measurement. Also in an open sea, they can alter the local flow.

To compound the above problems, wind and rain sensors at sea are exposed to spray and splash. At high latitudes, ice accretion is yet another problem. Moreover, in severe weather when data are vital, sensors and platforms are often damaged. Finally, the costs of servicing offshore platforms is enormous.

B. The Solution

Satellites may one day overcome the above difficulties, and provide global wind and rain measurements. Radar altimeters can already measure wind speed from satellites. Several satellites have already proved this capability. Perhaps future satellite sensors will provide rain rates as well. A network of polar satellites would then provide the needed coverage. Until we have operational satellite wind and rain sensors, however, hydrophones may offer an alternative. They are cheap, reliable, and isolated from the harsh sea-surface environment. They can rest on the seabed or hang below a buoy. Moreover, the underwater noise they record can potentially provide measurements of both wind speed and rain rate.

C. Earliest Studies

Knudsen et al., in 1948 provided the first evidence.[1] He showed that wind and rain are major contributors to undersea noise in the 1 to 30 kHz range. It was in this 1948 paper that he published the well known "Knudsen Curves." Since that time, these curves have been the reference for estimating underwater noise produced by wind. In 1959, Franz analyzed splashes in liquids as sound sources.[2] He produced another series of reference curves for underwater noise from rain's surface impact.

Figure shows both Knudsen's and Franz's curves. Frequency in kilohertz is the x-axis. Underwater noise level in decibels is the y-axis. Wind noise (dotted lines) increases with wind speed, and is higher in lower frequencies. Its slope is about -20 dB per decade of frequency.

Underwater rain noise (solid lines in Figure 1) also increases with rain rate. In contrast to wind noise, however, rain noise is fairly uniform over all frequencies. The difference in slope between wind and rain noise is important. It should allow one to estimate both wind speed and rain rate by measuring underwater noise at several frequencies.

D. Other Wind-Noise Studies

Many studies since Knudsen's early work validated his observations of underwater wind noise. For example, in 1954 Johnson made measurements off Mexico and Central America.[3] He confirmed Knudsen's wind-noise curves. Piggott in 1964 and Perrone in 1969 made measurements in the northwest Atlantic.[4,5] Once again, they noted the strong wind-speed dependence of low-frequency underwater noise. After the above studies defined the shape of wind-noise curves, researchers next tried to fit empirical expressions to these curves. In 1962 Wenz suggested underwater wind noise from 3 kHz to 10 kHz varied as the square of the wind speed.[6] In 1972 Crouch and Burt fitted Perrone's and Piggott's Atlantic wind-noise data.[7] Their expression for frequencies below 3 kHz was:

$$NL = B(f) + 10\ n \log V^2$$

where: NL = noise level (dB re 1 μPa),
B = noise level at 1 kt wind speed,
f = frequency,
n = constant,
V = wind speed (kt).

Their expression also suggested that noise level increases as wind speed squared.

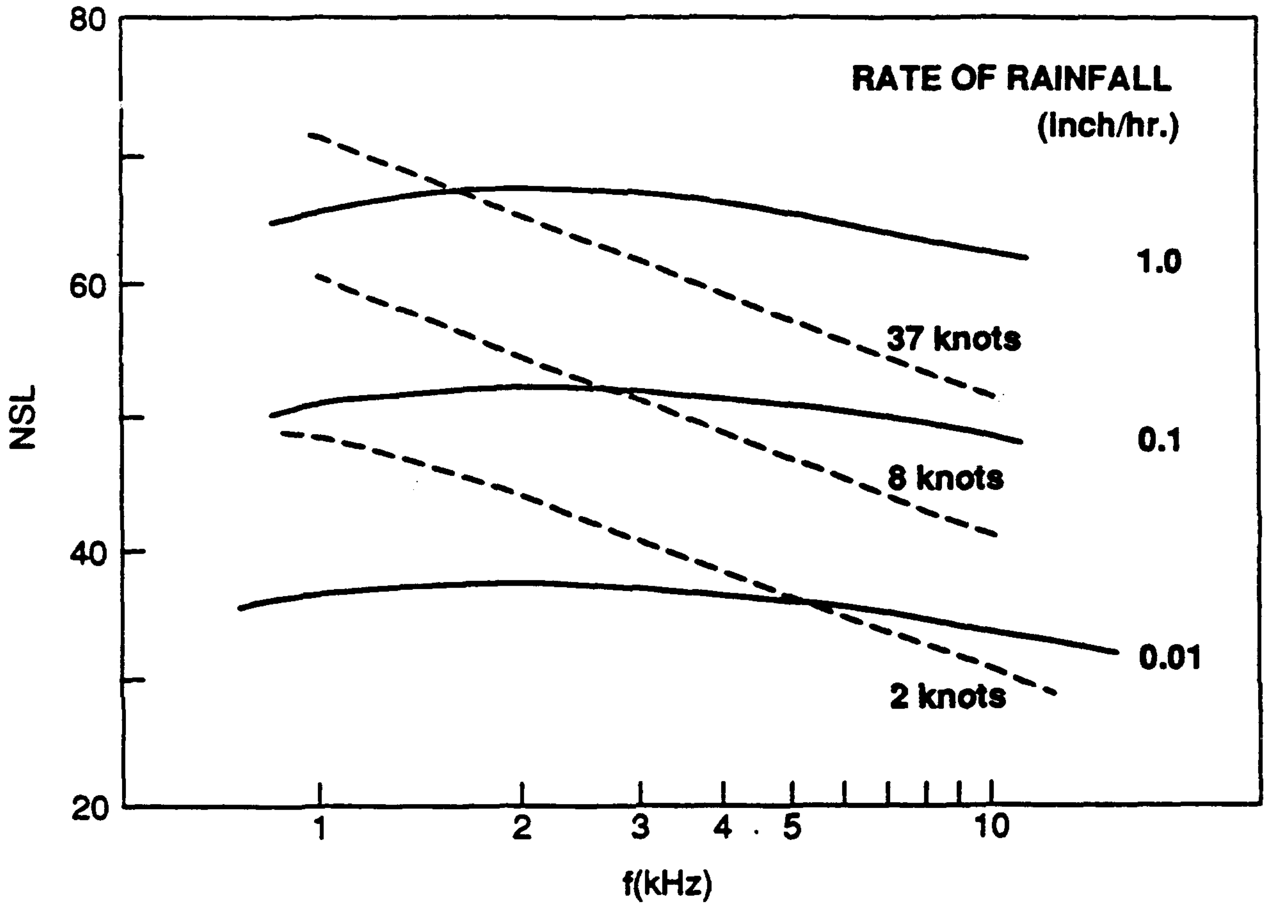

Figure 1. Underwater wind and rain noise from Knudsen (1948) and Franz (1959). Frequency (kHz) is the x-axis, and underwater sound level (dB) is the y-axis. Wind noise (dotted lines) increases with wind speed, and is higher at lower frequencies. Rain noise (solid lines) increases with rain rate uniformly at all frequencies.

By 1978, Shaw et al., also used the same expression at one frequency (5 kHz) to predict wind speed to within 5 kt of the measured values.[8] He derived his relationship at a deep water site in the western North Atlantic.

Evans et al., achieved an even better prediction in 1984.[9] They mounted a nondirectional hydrophone on the ocean floor in the equatorial Pacific. By monitoring three frequencies (4.3, 8.0, and 14.5 kHz), they could estimate wind speed to 2 kt using an expression similar to Crouch and Burt's.

Lemon et al., in 1984 extended Evans' wind-prediction relation to the continental shelf.[10] In this study they also compared underwater noise with rainfall measurements made at nearby stations. Their results agreed with Franz's early work.

Vagle et al., in 1990 derived a prediction equation of the form:

$$V = (SPL - a)/b$$

where: V = wind speed (m/s),
$SPL = 10^{NL/20}$,
NL = noise spectrum level (dB re 1 μPa corrected to 1 m depth),
a and b = frequency-dependent constants.[11]

In this study Vagle et al., *recommended a method for standardizing* hydrophone measurements to 1 m depth. They then tried their algorithm with data from other studies. Their depth-corrected wind speed estimates were within 1 kt for deep ocean waters, but did not hold for shallow coastal waters.

E. Other Rain-Noise Studies

Franz's work concentrated on rain-impact noise. He did both theoretical and laboratory work (in a water-filled tank). The field observations of Heindsmann et al., in 1954 in Long Island Sound confirmed Franz's work.[12]

In 1967 Bom made measurements in a shallow lake in Italy using frequencies from 0.3 kHz to 9.6 kHz.[13] He fitted his data with the expression:

$$NL = a + b \log R$$

where: NL = noise spectrum level (dB re 1 μPa),
a and b = frequency-dependent constants,
R = rain rate (inches per hour).

The rain rates predicted by this expression were appreciably higher than Franz's laboratory data. In 1986, Nystuen recorded rain noise data in a large lake in Illinois.[14] He found a rain-noise peak near 15 kHz.

Scrimger et al., in 1987 followed up on Bom's work with another lake study of rain noise.[15] They, like Nystuen, also noted a rain-noise peak. Theirs was at a somewhat lower frequency (13.5 kHz). Surrounding the peak was a steep falloff. The falloff was 60 dB per octave on the low frequency side, and 9 dB per octave on the high frequency side. They proposed a linear relationship between rain noise at this peak, and the log of the rain rate.

In 1987 and 1990 Nystuen and Farmer and Nystuen attempted to explain the rain-noise peak.[16,17] Rain drops produce underwater noise both through drop impacts and bubble trapping. Nystuen suggested that the impacts produced the spectral peak, and that the location of the peak changed as the wind varied the angle of impact. Recent studies by Prosperetti et al., and Pumphrey et al., also proposed a theory on the rain-noise peak.[18,19] Their theories suggest bubble trapping as the source. They argue that certain size drops, common in most rainfall, entrain bubbles that are the noise source.

Until recently, most of the underwater rain-noise measurements were in lakes. In 1989, however, Nystuen and Farmer measured rain noise in the ocean off Nova Scotia.[20] They found rain noise was identifiable even in strong winds.

Scrimger et al., followed with more open ocean work.[21] Their recordings were off Vancouver Island in British Columbia, Canada. They deduced a relationship between noise level and rain rate for various sea states and frequencies. They also confirmed the rain-noise peak, and showed a gradual reduction in this peak with increasing sea state. In 1990 Tan obtained very heavy (250 mm/hr) rain-rate noise in the Gulf of Mexico.[22] His study confirmed the high correlation between rain rate and underwater noise in heavy rain. He concluded that acoustical rain-rate measurement is possible at sea using frequencies in the range from 2 to 10 kHz.

From all of the above studies, several things are clear. First, much of the early work was in tanks and lakes. Its application to the open ocean is questionable. Second, although underwater wind noise is fairly well studied, combined wind and rain-noise studies are few. Finally, there is no agreement on a practical way to estimate wind speed and rain rate from a hydrophone.

F. This Study

The object of this work was to derive practical equations for estimating wind speed and rain rate from underwater noise. All available data in this and previous studies were used. The results showed practical wind speed equations are possible. However, rain-rate prediction is difficult.

II. METHOD

A. Region

For this experiment, underwater noise was recorded from a mooring located off Key Largo, Florida at 25°14.9'N, 80°10.9'W. The location is shown in Figure 2. The mooring was 10 km east of Key Largo in 50 m of water. A hydrophone was suspended 5.5 m off the bottom. Data were obtained between October 18 and November 20, 1988. In addition to underwater-noise data, wind speed and rain rates were also recorded on a lighthouse 3.7 km southwest of the mooring.

Typical weather consisted of fast-moving storms with moderate winds and heavy rain. During the deployment, six storms passed with wind speeds from 0 to 22 kt, and rain rates from 0 to 59 mm/hr.

Shipping and biological noise added to the underwater noise. Since the mooring was located only 10 km from the edge of a shipping lane, tankers, freighters, commercial, and recreational fishing vessels added noise. Finally, since the area is a marine sanctuary, there was abundant marine life present. Many of these animals, for example snapping shrimp, produce sound in the frequencies monitored in this study.[23]

B. Instruments

Underwater noise levels were recorded by a WOTAN instrument. This instrument contains a nondirectional wide-band hydrophone that records noise in 12 discrete frequency bands.[24] For this experiment, a 33-day time series was recorded. This series consisted of 30-second averaged noise levels for each of the 12 frequencies.

At the lighthouse, there were a variety of weather instruments. A Scientific Technology model ORG-505 optical rain gage collected rain-rate data.[25] A Young anemometer collected wind data.[26] A Sea Data WTR-10 weather station recorded the rain rate, wind speed, and direction.[27] Finally, a WSR-57 10 cm weather radar, based in Miami, tracked the rain cells.[28] From this radar, storm size, speed, and rain rates could be calculated from rain particle reflections.[29]

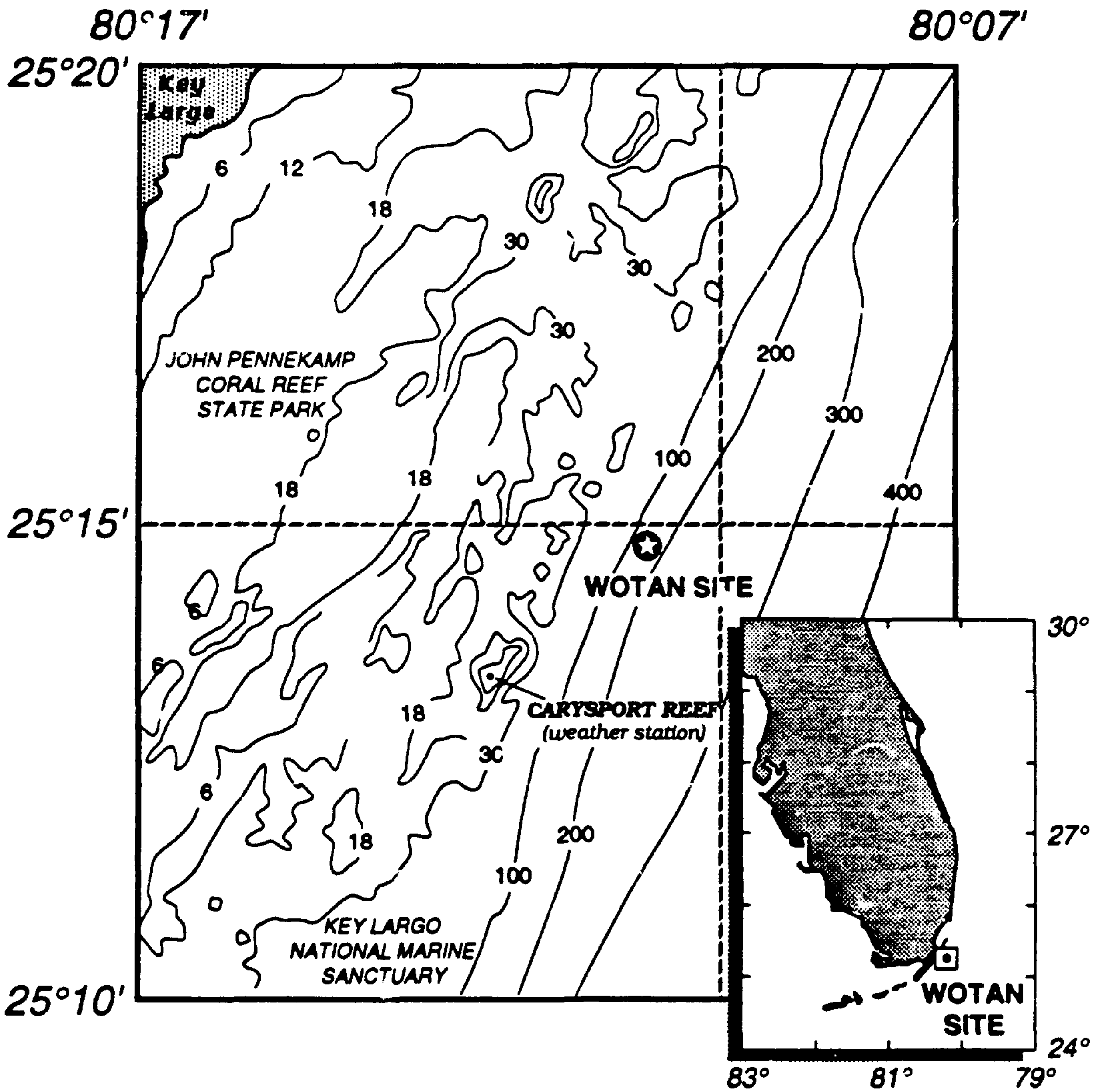

Figure 2. Location of experiment off south Florida at 25°14.9'N, 80°10.9'W. The mooring was 10 km east of Key Largo in 50 m of water (labeled WOTAN site in figure). The hydrophone was 5.5 m above the bottom. Wind and rain were recorded 4 km southwest of the mooring at Carysport Reef. Chart contours are in feet.

C. Data

Within the WOTAN, the hydrophone was connected to an amplifier and to 12 parallel filters with constant frequency/bandwidth ratios of 7. The 12 filters were centered on 0.5, 1, 2, 4, 8, 10, 12.5, 15, 17.5, 20, 25, and 30 kHz. The output of each filter was fed into a digital converter that produced a RMS value every 5 seconds. Six of these 5-second values were then averaged and an output was recorded every 30 seconds.

At the weather station, instruments sampled every 30 seconds, then calculated and recorded an average every 5 minutes. Longer sampling intervals are often used for wind, but rapidly changing rain rates required the 5 minute average.

In contrast to the scale of wind systems, rain systems are small. Hence, the 3.7 km separation between hydrophone and weather recorder could be ignored for the wind data, but could not be ignored for the rain data. Traveling rain cells would pass the two recording sites at different times. Thus the two sites would record rain at different times. The time differences were estimated by comparing the rain rate and noise data. The noise data was then shifted so the peak noise event matched the peak rain rate.[30]

Next the data were grouped according to wind speed and rain rate. This was done to reduce sampling variability and instrument errors and fluctuations. Wind speeds were grouped by calm (0 kt), light (1 to 10 kt), moderate (10 to 20 kt), and high (>20 kt). Rain rates were grouped by none (0 mm/hr), light (0 to 2 mm/hr), moderate (2 to 10 mm/hr), and heavy (>10 mm/hr).

Using the above groups, noise data were placed in the appropriate group, and then edited. The editor was designed to remove high noise transients (due to ships, animals, etc.). The noise levels at each frequency were checked for points exceeding two standard deviations from the group mean. If any record contained such points, it was discarded. This resulted in approximately 20% of the data being discarded for excessively high noise.

Finally, the remaining noise levels in each group were averaged. The result was eight sets of noise level versus frequency data. There was one set for high, moderate, light, and calm wind. The other set was for heavy, moderate, light, and no rain.

Using the above eight noise levels with 12 separate frequency bands, multiple regression was used to derive prediction equations for wind speed and rain rate.

III. RESULTS

A. Noise Levels

(1) Wind without rain

Figure 3 shows average wind noise grouped by calm, light, moderate, and high winds. These samples were all recorded during periods of no rain and hence contain no rain noise. Ten samples are included in each group.

Below 8 kHz noise increases with wind speed; above 8 kHz noise is unrelated to wind speed. High winds add about 10 dB at 0.5 kHz, and nothing above 8 kHz.

An analysis of variance was applied to the data in Figure 3. The object was to determine if the curves were statistically different. This analysis showed that the differences in the curves were not due to sampling variability (95% confidence level).

In summary, Figure 3 shows that increasing wind speeds significantly increase noise, especially below 8 kHz. Also, there is little difference in noise levels between calm and light wind.

(2) Rain

Figure 4 shows the grouped rain-rate curves. The groups are none, light, moderate, and heavy. There were 10 samples with no rain, 12 light rain, 11 moderate rain, and 7 heavy rain.

An analysis of variance was also applied to the rain data in this figure. The object was, as in the wind data, to determine if the differences in the curves were statistically significant. This analysis showed the differences in the curves were significant (95% level).

This figure also includes added wind noise. This is because rain and wind often occurred together in the data. To demonstrate this a group-mean wind was calculated within each rain group. This group mean for no rain was 12 kt, for light rain 13 kt, moderate rain 15 kt, and heavy rain 17 kt. Hence, wind speeds increase with rain rates in this data.

In summary, Figure 4 shows increasing rain rate increases noise in all frequencies. However, the differences in noise between no rain and light rain are minor. Finally, the figure also contains some added wind noise. This added noise must be addressed for comparisons with other studies.

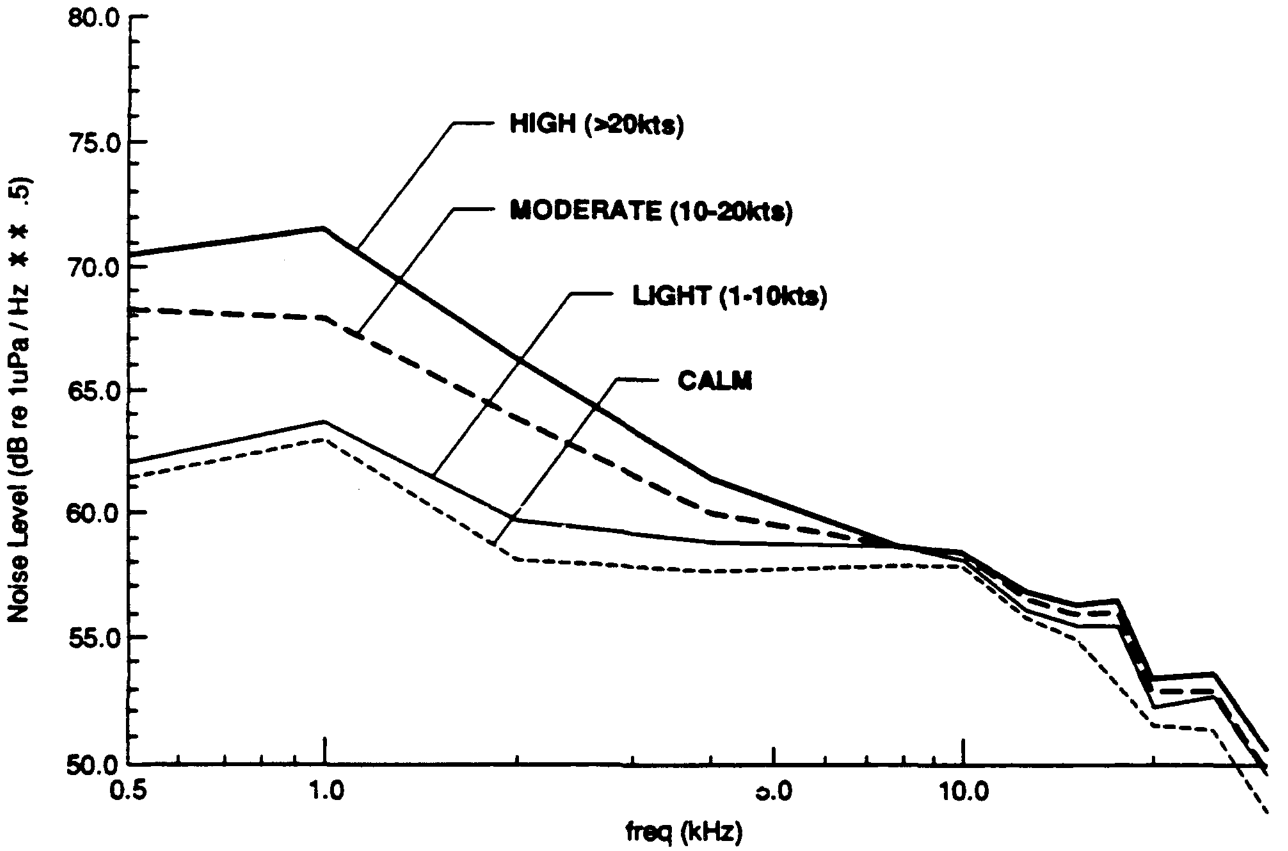

Figure 3. Underwater wind noise from this study. Data were grouped by calm (0 kt), light (1-10 kt), moderate (10-20 kt), and high (>20 kt) winds. There was no rain when the 10 samples in each of these groups were recorded. The figure shows that noise increases with wind speed at frequencies below 8 kHz.

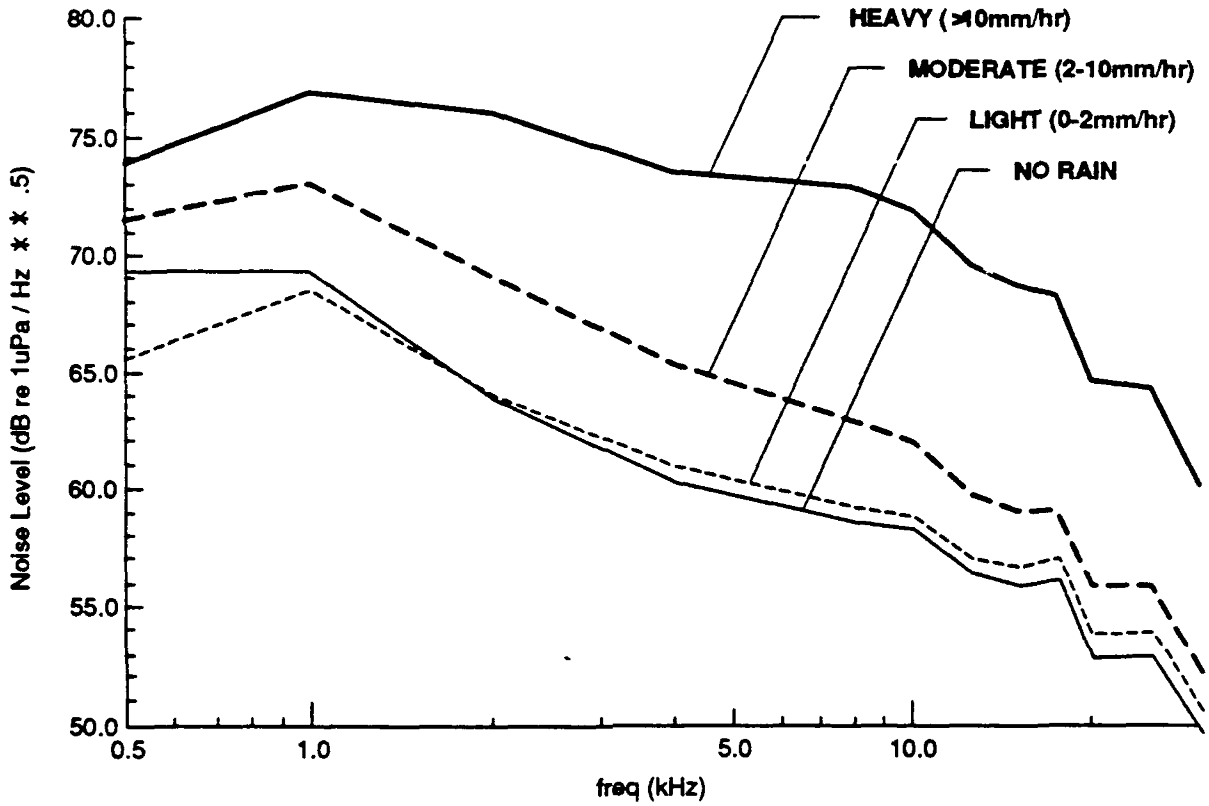

Figure 4. Underwater rain noise from this study. Data were grouped by no rain (0 mm/hr), light (0 to 2 mm/hr), moderate (2 to 10 mm/hr), and heavy (>10 mm/hr). There were approximately 10 samples in each group. The figure shows higher rain rates increase noise at all frequencies.

B. Prediction Equations

As the next step, regression was used to derive wind and rain-rate prediction equations from the grouped data (Figures 3 and 4). The form of the equations used to fit the data was selected to match successful fits by previous workers. For example, Vagle et al., fit their data with equations that were linear in sound pressure level.[11] Evans et al., Lemon et al., and Scrimger et al., however, used equations with sound pressure level raised to a power.[9,10,21]

In this study, both of the above types of prediction equations were tried. Step wise, multiple regression was used. Wind speed and rain rate were the dependent variables. Noise levels, differences between noise levels, and noise levels raised to a power at each frequency band were the independent variables. The objective was to predict wind speed and rain rate using the simplest equations employing the minimum number of noise-level bands.

(1) Wind without Rain

Each of the four wind groups in Figure 3 was assigned its average value (0, 5.0, 14.7, and 21.0 kt). Combinations and powers of the noise levels at the 12 frequencies were the predictor variables.

The simplest wind-without-rain prediction equations used only the 2 kHz noise level. The equation was:

$$WS = a + b * SPL(2\ kHz)$$

where: WS = wind speed in kt,
a = -12 kt,
b = $1.6*10^{-2}$ kt/μPa,
SPL = sound pressure level in μPa.
The standard error of estimate was 1 kt.

The simplest nonlinear equation was:

$$WS = a * SPL(2\ kHz)^{2.8}$$

where: WS = wind speed in kt,
a = $1.3*10^{-8}$ kt/μPa,
SPL = sound pressure level in μPa.
The standard error of estimate was 3 kt.

From the above standard errors, the linear equation provides the better fit to the wind-without-rain data from this study.

(2) Rain

Next, the rain-rate prediction equation was derived for this study using the same technique. The linear rain-rate prediction used only the 8 kHz noise level. It was:

$$RR = a + b * SPL(8\ kHz)$$

where: RR = rain rate in mm/hr,
a = -6.1 mm/hr,
b = $7.3*10^{-3}$ (mm/hr)/μPa,
SPL = sound pressure level in μPa.
The standard error was 0.4 mm/hr.

The nonlinear rain rate prediction equation was:

$$RR = a * SPL(8\ kHz)^{2.2}$$

where: RR = rain rate in mm/hr,
a = $2.0*10^{-7}$ (mm/hr)/μPa,
SPL = sound pressure level in μPa.
The standard error was 3.0 mm/hr.

From these standard errors, the linear equation also provides the better fit to the rain data from this study.

(3) Wind with Rain

Finally, a wind-with-rain prediction equation was derived. This was done by going back to the original data and sorting out all occurrences of simultaneous wind and rain. These noise data were then used in the regression. Wind speed was the dependent variable, and combinations of noise levels at all frequencies were the independent variables.

The resulting wind-with-rain prediction equation was linear, and required two noise levels. The equation was:

$$WS = a + b * SPL(2\ kHz) + c * SPL(8\ kHz)$$

where: WS = wind speed in kt,
a = 12 kt,
b = $6.5 * 10^{-4}$ kt/μPa,
SPL = sound pressure level in μPa,
c = $5.8 * 10^{-5}$ kt/μPa.
The standard error of estimate was 5 kt.

In summary, for the data from this study, all derived prediction equations were linear. Wind without rain required the 2 kHz noise level; rain rate required the 8 kHz noise level; wind with rain required both the 2 and 8 kHz noise levels.

C. Comparisons with other studies

(1) Noise

a. Wind

i. Knudsen

Figure 5 shows the depth-corrected data from this study plotted with Knudsen, Perrone, and Scrimger et al.[1,5,15]

Knudsen's measurements were at different depths in coastal regions off the U.S. East and West coasts, Hawaii and Great Britain. His curves show a steady decrease in noise at higher frequencies. They also show a uniform increase in noise from light, to moderate, to high winds. Compared to the data in this study, Knudsen's show less high-frequency noise, and more wind-speed separation. Figure 6 shows these differences more clearly. This figure was derived by subtracting Knudsen's moderate wind data from the moderate wind data from this study.

ii. Perrone

Perrone recorded low frequency noise (less than 3 kHz) in the open ocean south of Bermuda. Figure 5 shows his noise levels are lower that those of this study.

iii. Scrimger

Scrimger collected data in 35 m of water in a large lake. His data have lower noise levels for light winds, but they agree with this study in moderate winds at lower frequencies. Nevertheless, his high frequency noise levels are always lower than in this study.

iv. Wenz

Figure 7 shows coastal-noise data of Piggott, Wenz, and Farmer and Lemon plotted with this study.[4,6,31] Wenz's noise levels are from several shallow (less than 200 m) coastal locations. They agree with this study in midrange frequencies, but are also lower at high frequencies.

v. Piggott

Piggott's low-frequency data were collected in 55 m of water off Nova Scotia. He shows larger separations between wind speeds than the data in this study.

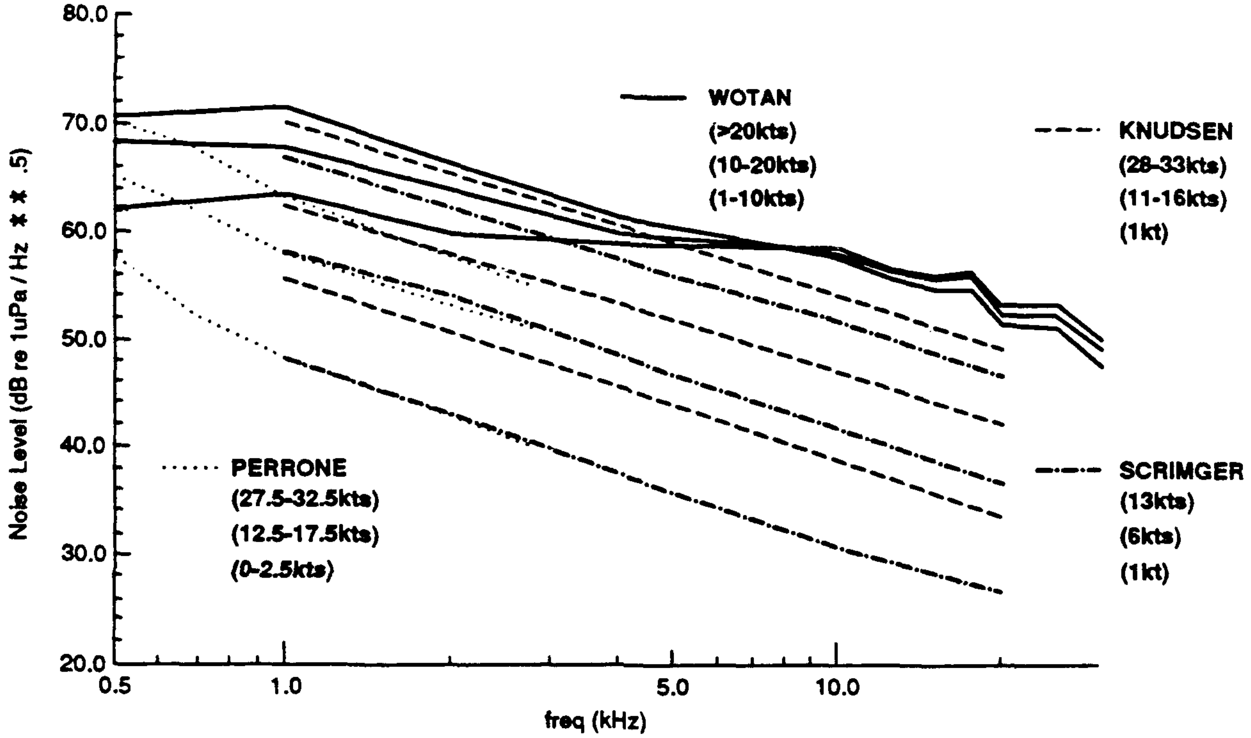

Figure 5. Underwater wind-noise from this study plotted over data by Knudsen, Perrone, and Scrimger et al.[1,5 15] These open-ocean and lake studies show less high-frequency noise.

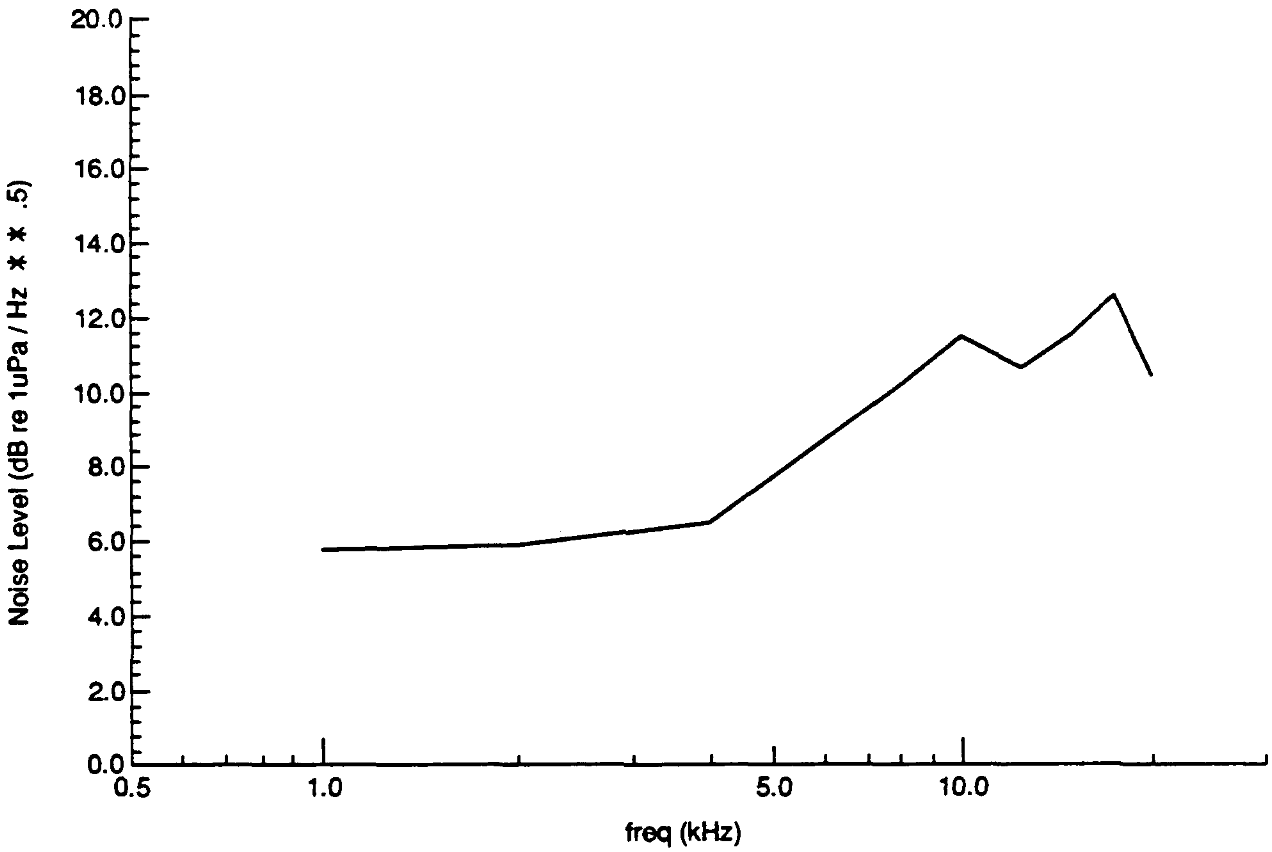

Figure 6. Differences in underwater wind noise between this study and Knudsen's. This figure was calculated by subtracting Knudsen's moderate-wind noise values from this study. The resulting plot shows the high level of high-frequency noise in this study.

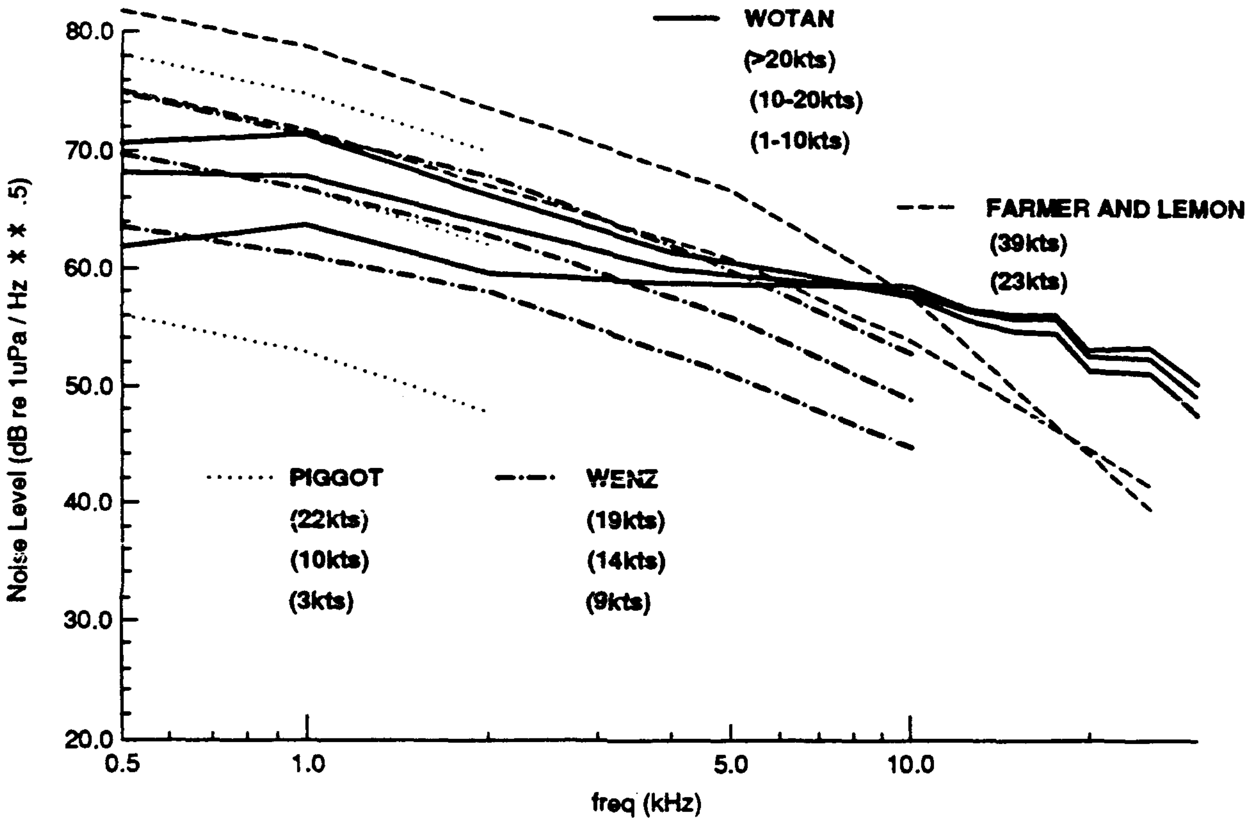

Figure 7. Underwater wind noise from this study plotted over data by Piggott, Wenz, and Farmer and Lemon.[4,6,30] These coastal-ocean data match this study better than open-ocean and lake data.

vi. Farmer and Lemon

Farmer and Lemon's noise levels were collected in high winds in 250 m of water off British Columbia. Their high wind-speed noise curve (23 kt) agrees with the high wind noise levels for this study below 8 kHz. Their highest wind speed curve (39 kt) shows noise levels continuing to increase with higher winds. However, even in the highest winds, high-frequency noise is less than in this study.

vii. Summary

The wind data from this study compare best with other coastal data (Wenz, Piggott, and Farmer and Lemon). However, all other studies contain less high frequency noise. This noise may be due to shrimp. Figure 8, which shows snapping shrimp can add 20 dB of high frequency noise, supports this suggestion.

b. Rain

i. Franz

Figure 9 shows the data from this study plotted with Franz, Bom, and Tan.[2,13,22] Franz's data are based on theory and tank results with no wind. His noise levels are flat, and show a uniform (15 dB) difference between light, moderate, and heavy rain.

The data in this study, however, show much higher noise levels for comparable rain rates, and less separation between the rain levels. One explanation is the added wind noise present in this study.

To reduce this added wind noise, the moderate wind-noise curve in Figure 3 was subtracted from each rain curve in Figure 4. The resulting "wind-corrected" rain curves are shown in Figure 10. These corrected curves now more closely match the other studies.

ii. Bom

Bom's data were collected in a shallow (10 m) lake in Italy. They show a more modest difference (10 dB) between rain rates, and lower noise levels (5 to 10 dB) than in this study.

iii. Tan

Tan's data were collected in the Gulf of Mexico in 13 m of water. His noise levels match those in this study at mid to high frequencies.

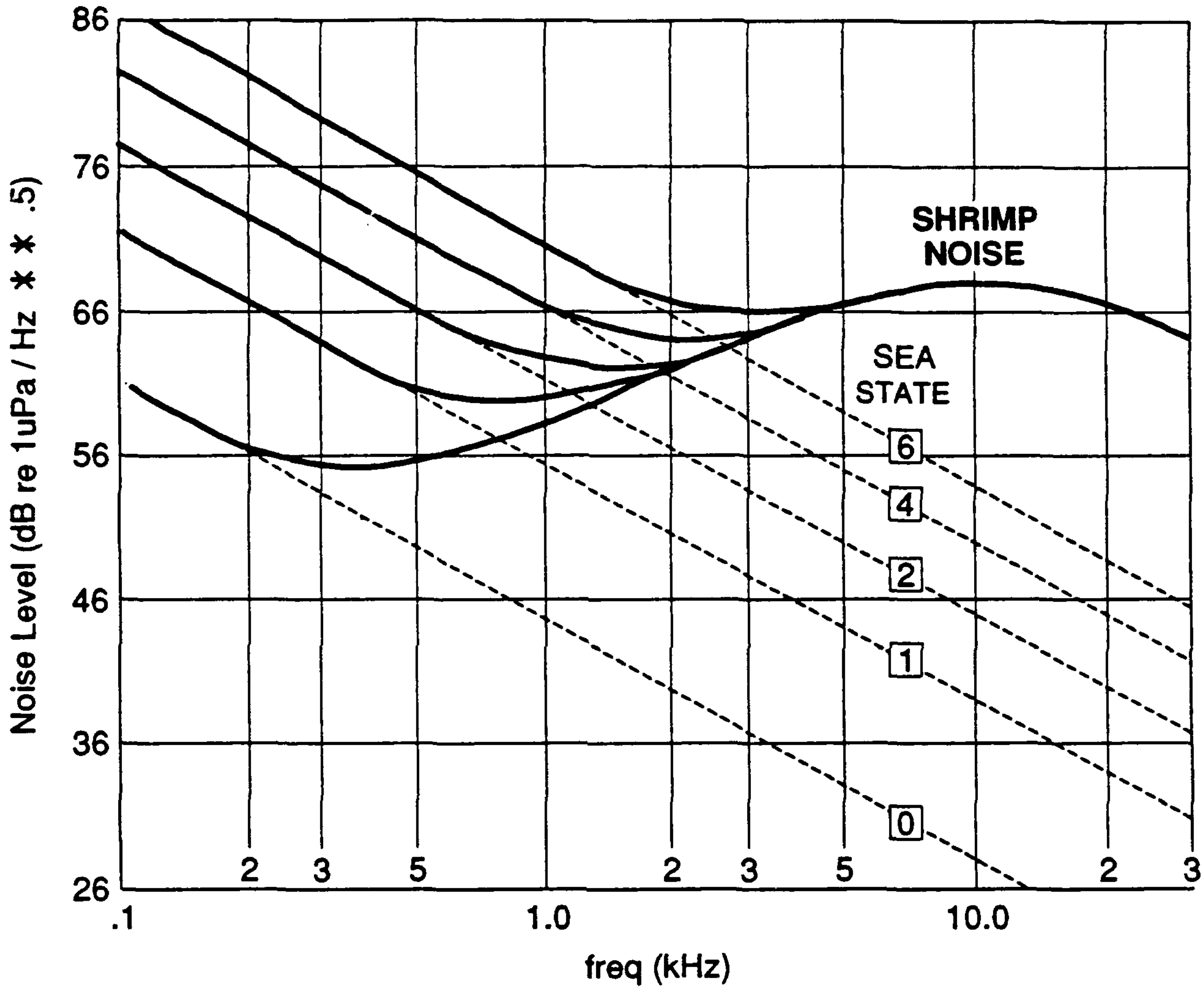

Figure 8. Underwater noise from snapping shrimp. Shrimp add high frequency noise under all conditions.

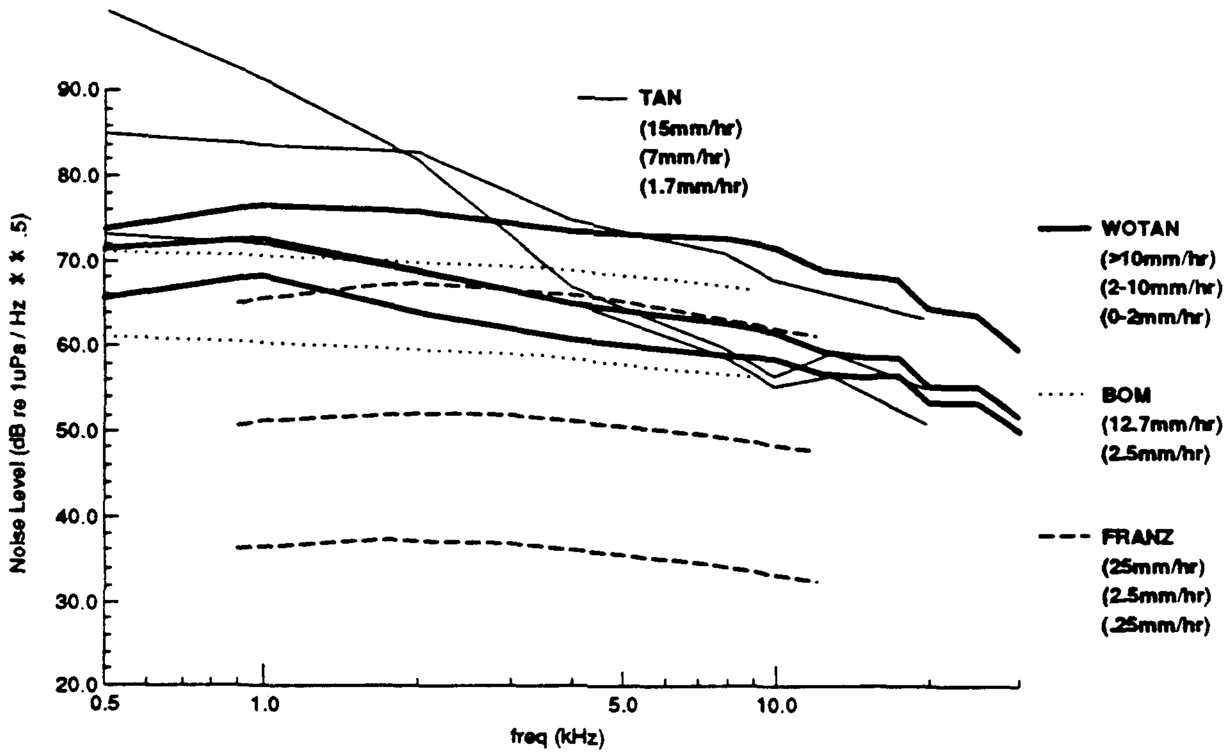

Figure 9. Underwater rain noise from this study plotted with those of Franz, Bom, and Tan.[2,13,22] All curves have similar shape, but noise levels from this study are higher for similar rain rates.

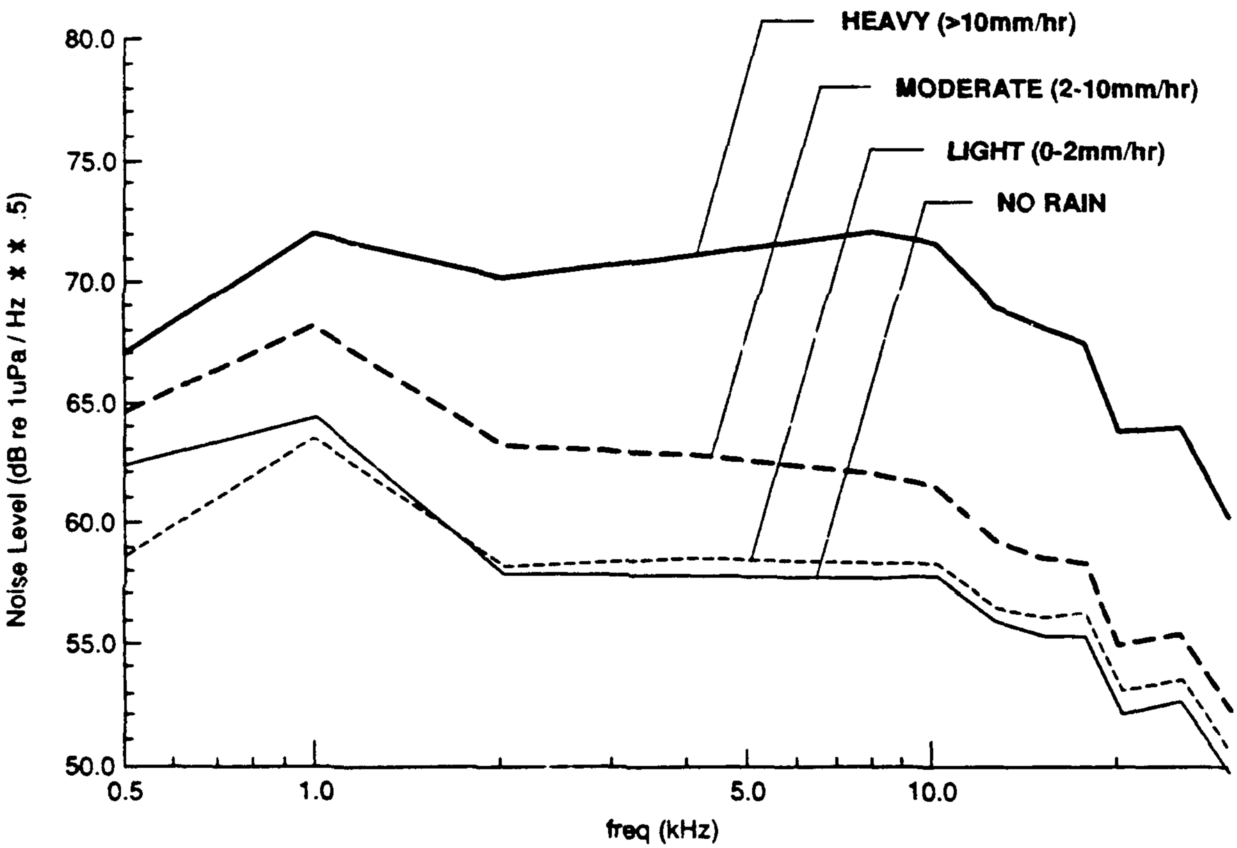

Figure 10. Underwater rain noise from this study corrected for wind noise. The moderate wind noise in Figure 3 was subtracted from each rain noise curve in Figure 4. The resulting curves more closely match rain noise from other studies.

iv. Nystuen

Figure 11 shows data from this study plotted with Nystuen, Scrimger et al., Nystuen and Farmer, and Scrimger et al.[14,15,16,21] Nystuen recorded an extraordinary rain rate of 260 mm/hr in a lake. His hydrophone, in 8 m of water, recorded noise levels greater than any other rain study. Even in such heavy rain, a 15 kHz frequency peak could still be detected.

v. Scrimger

Scrimger's 1987 data were collected in 35 m of water in a lake. These data, for light rain and light wind, show high variability. He also confirmed the 14 to 15 kHz rain-noise peak.

Scrimger's 1989 coastal data were in 55 m of water off British Columbia. These light wind data also show a 15 kHz rain peak that grows with rain rate.

vi. Nystuen and Farmer

Nystuen and Farmer's data were collected in 35 m of water in a lake. These data show that light winds (7 kt) mask the 15 kHz rain-noise peak.

vii. Summary

In summary, the rain data taken in this study show higher noise levels than other studies. Judging from the no-wind rain studies, this added noise is probably due to wind. If a mean-wind noise curve is subtracted from each rain curve in this study, the results more closely match other studies.

Another difference in rain noise curves from this study is the absence of the 14 to 15 kHz peak. Judging from Nystuen and Farmer's data, this is also probably due to wind masking.

(3) Prediction Equations

a. Wind without Rain

Next, wind-without-rain prediction equations from five other studies were tested with the data from this study. Of the five equations, only Vagle's was linear in sound-pressure level. The rest were given in noise level (dB), and hence were nonlinear in sound-pressure level. Table 1 compares the predictions of Crouch and Burt, Shaw, Evans, Lemon, and Vagle to the data from this study.

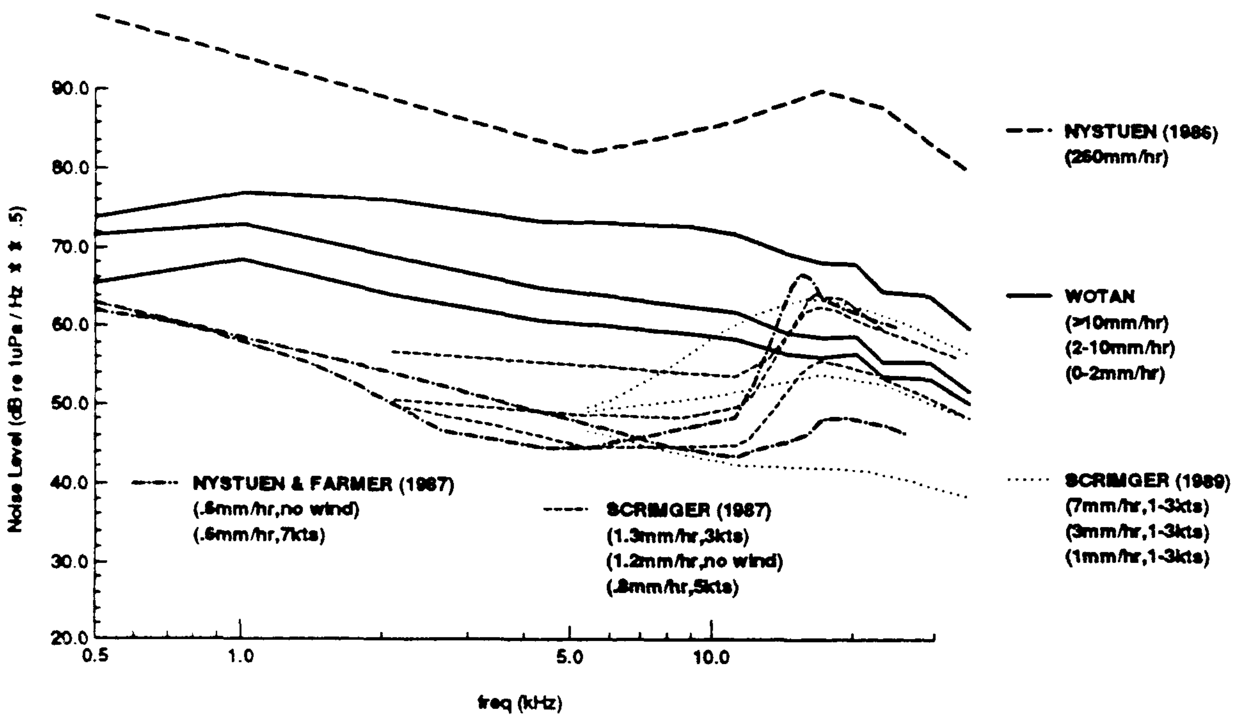

Figure 11. Underwater rain noise from this study plotted with the low-wind rain noise of Nystuen, Scrimger et al., Nystuen and Farmer, and Scrimger et al.[14,15,16,21] All low-wind rain noise studies show noise peaks near 15 kHz. This study, with moderate to high winds during rain, showed no such peak.

i. Crouch and Burt

Crouch and Burt derived their noise level equation in 1972 by fitting both Piggott's 1964 and Perrone's 1969 study. Measurements were in the range of 11 Hz to 2.8 kHz. When their equation was used on the data from this study; however, predicted winds were much too high. Since their source data contained only very low noise levels, their equation is probably useful only in low noise environments.

Table 1. Wind-speed prediction equations from other sites tested with data from this site. The equations use underwater noise level in dB (NL) or sound pressure level in μPa (SPL) at the frequency listed in column 3. The constants are a and b. Wind-speed equations from other sites worked poorly at this site.

Study	Prediction Eq. for Wind Speed	Freq.(kHz) used in equation	Predicted Wind (kt)		
			Lgt.	Mod.	High
This study ('91)	V = a+b(SPL1)	2.0	5	15	22
Crouch & Burt ('72)	20nlogV = NL-b	2.8	55	70	89
Shaw ('78)	20logV = 1.01(NL)-30.4	5.0	29	32	36
Evans ('84)	20logV = a(NL)+b	4.3	12	19	22
Lemon ('84)	20logV = a(NL)-b	4.3	18	20	22
Vagle ('90)	V=(SPL-a)/b	8.0	32	32	32

ii. Shaw

Shaw's equation was derived using 5 kHz data collected in the western North Atlantic. His equation also predicts higher wind speeds than observed in this study. Again, his records were from the deep ocean with their low noise levels. Hence, his equation is also more suitable for lower noise environments.

iii. Evans

Evans' equation was derived from measurements at 4.3, 8.0, and 14.5 kHz in the equatorial Pacific. His equation worked well on the data from this study.

iv. Lemon

Lemon used the same frequencies as Evans to predict noise levels from coastal measurements off the west coast of Canada. His equation works well on the moderate and high wind data in this study.

v. Vagle

Vagle's sound-pressure level equation did not work for this study. He used 8 kHz as the predictor frequency, and this study showed no wind noise effect at that frequency.

vi. Summary

Each study to date has resulted in different empirical fits to observed wind-without-rain noise data. Only one of the previous five studies produced an equation that would work for the data of this study. All others predicted wind speeds that were too high.

b. Rain

There have been only two studies that derived rain-rate prediction equations. Bom made an attempt in 1969, and Scrimger in 1989. Both were nonlinear in sound-pressure level. Table 2 compares their predictions using the data recorded in this study.

i. Bom

Bom collected data in a small lake from 0.3 to 9.6 kHz. He then fit a separate equation for each octave. His 4.8 to 9.6 kHz equation worked well on this data for moderate to heavy rain. However, it overpredicts light rain, probably because his equation was based on low ambient noise levels.

Table 2. Rain-rate prediction equations from other sites tested with data from this site. The equations use noise level in dB (NL) or sound pressure level in μPa (SPL) at some frequency (given in column 3). Constants are a or b. Bom's equation, the only one based on a variety of rain-rates, worked fairly well.

Study	Prediction Eq. for Rain Rate	Freq.(kHz) used in equation	Predicted Rain (mm/hr) Lgt.	Mod.	Hvy.
This study ('91)	R = a+b(SPL)	8	0.5	3.9	25.8
Bom ('68)	log R = (NL-a)/b	4.8-9.6	4.1	6.9	28.9
Scrimger ('89)	log R = (NL-a)/b	8	49.5	726	HIGH

ii. Scrimger

Scrimger's coastal ocean study was off British Columbia. He measured at 5, 8, 15, 20, and 30 kHz. He added sea state as another independent variable. To compare with this study, his equation for 8 kHz and sea state 3 was used.

Using these values, Scrimger's equation predicted extremely high rain rates. Since his data were all collected at low rain rates, the equation cannot be extrapolated to the high rain observed in this study.

iii. *Summary*

Of the above two rain-rate prediction equations, the one based on a variety of observed rain rates fit this study. The one based only on light rain did not.

D. Universal Prediction Equations

The studies reviewed above all derived site-specific prediction equations. When these equations were applied to the data of this study, most failed. In an attempt to derive more widely applicable equations, data from this and all other studies were combined and fitted. Wind noise data from Knudsen, Piggott, Perrone, Wenz, Scrimger et al., and Farmer and Lemon were used.[1,4,5,6,15,31] Rain noise data was from Bom, Scrimger et al., Nystuen and Farmer, and Tan.[13,15,16,22] As before, regression was used. Wind speed or rain rate were the dependent variables. Various combinations and powers of noise levels at each frequency were the independent variables.

1) Wind without Rain

The optimum wind-without-rain prediction equation from all the combined data used only the 2 kHz noise level. The equation was:

$$WS = a + b * SPL(2\ kHz)$$

where: WS = wind speed in kt,
a = 4.0 kt,
$b = 7.0*10^{-3}$ kt/μPa,
SPL = sound pressure level in μPa.

The standard error of estimate for this equation was 7 kt.

(2) Rain

The rain-rate prediction equation for the data from all studies was derived using the same methods. The optimum equation was linear and used both the 2 kHz and the 8 kHz noise bands. The equation was:

$$RR = a + b * SPL(2\ kHz) + c * SPL(8\ kHz)$$

where: RR = rain rate in mm/hr,
a = -11 mm/hr,
$b = 2.7*10^{-3}$ (mm/hr)/μPa,
SPL = sound pressure level in μPa,
$c = 5.7*10^{-3}$ (mm/hr)/μPa.

The standard error of estimate was 20 mm/hr.

(3) Wind with Rain

The optimum wind-with-rain equation was also linear and used both the 2 kHz and the 8 kHz noise bands. The equation was:

$$WS = a + b * SPL(2\ kHz) + c * SPL(8\ kHz)$$

where: WS = wind speed in kt,
a = 7.7 kt,
$b = 2.0*10^{-4}$ kt/μPa,
SPL = sound pressure level in μPa,
$c = 2.5*10^{-4}$ kt/μPa.

The standard error of estimate was 6 kt.

(4) Summary

In general, the derived prediction equations based on data from this and all other studies were linear. These equations are listed in Table III. The wind-without-rain equation required the 2 kHz noise band. The rain and wind-with-rain equations required both the 2 and 8 kHz noise bands.

Table 3. Wind and rain prediction equations derived from all data combined. Sources were all published studies. Sound pressure levels (SPL) at either 2 or 8 kHz were the best predictors. Errors from fitting these combined data sets (last column) were large.

Condition	Equation	Standard error
Wind (no rain)	$WS= 4.0 + 7.0*10^{-3} * SPL(2\ kHz)$	7 kt
Rain	$RR= -11 + 2.7*10^{-3} * SPL(2\ kHz)+ 5.7*10^{-3} * SPL(8\ kHz)$	20 mm/hr
Wind (with rain)	$WS= 7.7 + 2.0*10^{-4} * SPL(2\ kHz)+ 2.5*10^{-4} * SPL(8\ kHz)$	6 kt

IV. CONCLUSIONS

A. Noise Levels

(1) Wind

The underwater noise recorded in this study differs from previous studies. The major difference is added high frequency noise. Since the data in this study were edited to remove intermittent noise, the added high frequencies must be relatively steady.

Because this was the only study in a tropical, coastal environment, marine life may be the source of this noise. Snapping shrimp are the likely candidates. They are abundant in the surrounding waters, and produce high-frequency noise. They will probably add high-frequency background noise in any tropical coastal area.

Aside from these added high frequencies, however, noise levels recorded for this study compare well with other coastal noise data.

(2) Rain

Rain noise from this study also differs from other studies. It contains more low-frequency noise. Since winds usually accompanied rain, wind is the likely source. Wind noise is probably also responsible for masking the high-frequency peak that most studies have found during rain without wind. For practical applications, however, wind-contaminated rain noise is normal.

The high-frequency noise in the wind data, blamed on shrimp, was not evident in the rain data. It was probably masked by the high-frequency noise from the rain itself.

Another characteristic of this study is the similarity of no-rain and light-rain noise. High coastal noise masks light rain noise. Measuring light rain is possible only in quiet lakes. Hence, underwater noise measurements in coastal regions are limited to estimating moderate to heavy rain.

B. Prediction Equations

(1) From this Study

a. Wind without rain

The optimum wind-without-rain prediction equation, based on data from this study, was linear. It used noise level recorded at one (2 kHz) frequency, and had a standard error of only 1 kt. However, this equation was different from all other locally derived equations. Most likely, each prediction equation is site-specific, and varies depending on the background noise at the recording site.

b. Rain

The optimum rain-rate prediction equation was also linear. The equation used only the noise level recorded at 8 kHz, and had a standard error of only 0.4 mm/hr. However, it could not predict low rain rates.

c. Wind with Rain

The wind-with-rain prediction equation required both the 2 kHz and the 8 kHz frequency. No other study to date has proposed a wind-speed equation for use during rain. Hence, the limitations of this equation will require more studies that measure simultaneous wind and rain.

(2) From all studies

Universal prediction equations were attempted by fitting the data from this and all coastal and open ocean sites. The object was to discover more widely applicable equations.

a. Wind without Rain

The derived universal wind-without-rain prediction equation gave only fair estimates of wind speed in the study region. Using this equation with a hydrophone would not provide quality wind data.

b. Rain

The universal rain equation did not work in the study region. Heavy rain cannot be predicted with any degree of accuracy. Only fair estimates of light and moderate rain rates could be obtained. The equation could be used, however, for determining the presence or absence of rain.

c. Wind with Rain

The universal wind-with-rain equation also gave only fair estimates of wind speed. Again, the results would not be good enough for routine weather observations.

C. Overall

This study attempted to derive practical wind speed and rain rate prediction equations. These equations were to be used with hydrophones measuring underwater noise. The hope was that the same equations would work in any ocean region.

The attempt was only partially successful. The site-specific study done in this paper did provide accurate wind speed and rain-rate prediction equations. However, when an attempt was made to derive equations that worked for all sites, prediction errors grew. The resulting equations were of marginal value. Apparently unique *local background noise* defeats the idea of universal equations.

In summary, for the best wind and rain prediction equations, site-specific studies are required. How specific the study has to be is unknown. Perhaps sites can be generalized to regions such as "tropical-coastal." As the region is expanded, the prediction equation accuracy would then decrease. Future studies will have to address the possibility of regional equations.

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Equations for estimating wind speed and rain rate from underwater noise are derived in this paper. Data from both this study and other published studies were used.

Data for this study were collected during October and November 1988 off south Florida in 50 m of water. Noise levels at 12 frequencies from 0.5 to 30 kHz were recorded, edited, and grouped. Regression was used to derive site-specific prediction equations for wind speed and rain rate. The best-fit equations were all linear in sound-pressure level. The best wind-speed predictor, without rain, was the 2 kHz frequency. The best rain-rate predictor was 8 kHz. The wind-speed predictor, during rain, required both the 2 and 8 kHz frequencies.

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